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NATURE OF GALLERIES, DURABILITY OF BORING SCARS, AND DENSITY OF *XYLOTRECHUS VILLIONI* (VILLARD) LARVAE (COLEOPTERA: CERAMBYCIDAE), ON CONIFEROUS TREE TRUNKS[1]

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Abstract.—Spatial distributions and shapes of "whirl-like" scars on the trunks, made by gallery formation of mature larvae of *Xylotrechus villioni* (Villard) (Coleoptera: Cerambycidae), a primary borer of *Abies* and *Picea* coniferous trees in Japan, were investigated at an *Abies firma* Sieb. et Zucc. plantation in Hachiôji, Tokyo Pref., an *A. firma* natural stand in Miyama, Kyoto Pref. and an *A. sachalinensis* (Fr. Schm.) Mast. plantation in Imakane, Hokkaidô. Although all the forests investigated showed cumulative "whirl-like" scars on the tree trunks, a low density of existing larvae was inferred from the analyses of the locations and shapes of these scars. Mortality throughout the larval stages, as well as between the final phase of larva and the adult emergence, was suggested. Trunk analysis of a damaged *A. firma* tree showed that a "whirl-like" scar can remain on the trunk surface for as long as 27 years after the formation of the larval gallery. The most susceptible class of *Abies* trees had a diameter at the breast height of 35–45cm. "Whirl-like" scars were distributed more densely in the lower part of the trunks.

Key Words.—Insecta, Cerambycidae, *Xylotrechus villioni*, larval gallery, spatial distribution, conifers, *Abies*

Xylotrechus villioni (Villard), a cerambycid beetle endemic to Japan (Fig. 1), is a primary borer of coniferous tree species, mostly of the genera *Abies* and *Picea* (Iwata et al. 1990). This species is probably the largest member of the tribe Clytini (subfamily Cerambycinae), with its adult body length being 20–26 mm in males and 25–30 mm in females. Although this species, insofar as historically recorded, once had an outbreak and its larvae caused serious damage on *Abies sachalinensis* (Fr. Schm.) Mast. plantations in Hokkaidô (Kamijo et al. 1970, Kamijo & Suzuki 1973), adult beetles, as well as larvae, are found only rarely. This low density makes direct observations difficult, and little is known about the bionomics and ecology of this species (Iwata et al. 1990).

Larvae bore under the bark of the trunk and branches, and larval galleries cause cicatricial scars, which become more evident on the trunk as the tree cures the

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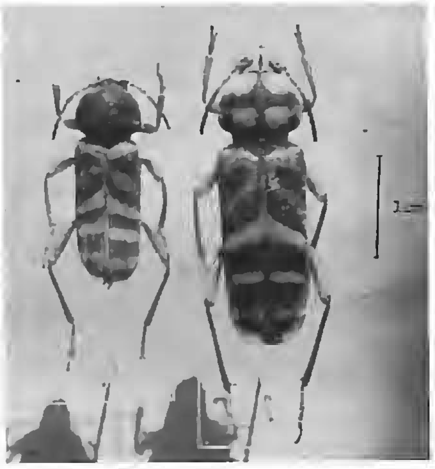

Figure 1. *Xylotrechus villioni* adults from Mt. Kasuga, Nara. Reproduced from Iwata (1991). left, male; right, female.

damage through cicatrization with phloem recovery. These scars remain recognizable for a long period of time because the complete recovery of outer phloem takes many years after the appearance of a scar.

The larval boring consists of 5 phases (Kamijo & Suzuki 1973, Iwata et al. 1990), of which Phase 4, attributed to mature larva, is characterized by the "whirl-like" gallery (Fig. 2), which is peculiar to this species and presumably made as a guard against resin exudation (Iwata et al. 1990, Iwata 1991).

Every scar with a straight, sinuate or "whirl-like" appearance found on *Abies* and *Picea* trunks in Japan is almost always accompanied by a gallery with tightly packed fine frass, which characterizes boring by a clytine cerambycid. As no other clytine species that attacks living conifers is known from Japan, the presence of such scars on coniferous trunks in Japan always indicates attacks by *X. villioni.*

Formation of a "whirl-like" scar (Fig. 3) on the trunk surface is caused through "whirl-like" gallery formation, and their distribution reflects the historical spatial distribution of the insect. Studying the "whirl-like" scars caused by *X. villioni* larvae may contribute to its enigmatic biology.

This paper reports the nature and the spatial distribution of *X. villioni* larval galleries on coniferous tree trunks.

Figure 2. "Whirl-like" gallery (arrowed) made by a *X. villioni* mature larva on a dead *Abies mariesii* tree-trunk, Hinoemata, Fukushima Pref.

Figure 3. "Whirl-like" scar (arrowed) made through gallery formation of a *X. villioni* mature larva on a living *Abies firma* tree-trunk, Mt. Kasuga, Nara. Reproduced from Iwata (1991).

Materials and Methods

Study sites.—Investigations were carried out at three sites, (A): an *Abies firma* Sieb. et Zucc. plantation in Tama Forest Science Garden, FFPRI (MAFF), Hachiôji, Tokyo Pref. (about 0.5 ha in extent, northeast-inclined, alt. 220 m) in Sep–Nov 1990; (B): an *A. firma* natural stand in Ashiu Kyoto University Forest (Section 33), Miyama, Kyoto Pref. (about 0.6 ha in extent, southwest-inclined, alt. 450m) in Aug 1990; and (C): an *A. sachalinensis* plantation in Kanahara, Imakane, Hokkaidô (about 0.3 ha in extent, flatland, alt. 80 m) in Aug 1991. The large-scale damage in the *A. sachalinensis* plantations in Imakane (C) and the damage in the *A. firma* plantation in Hachiôji (A), caused by *X. villioni*, have previously been documented (Ganda et al. 1986, Makihara et al. 1995, respectively).

Spatial distributions and morphology of "whirl-like" scars.—The following were recorded for each tree at all sites: (1) diameter at the breast height (DBH), (2) presence of resin exudations (a possible index of larval existence), (3) presence of straight and sinuate scars, and (4) presence of "whirl-like" scars on the trunk. These give the spatial distribution of "whirl-like" scars in relationship to tree's DBH, as well as the density of the existing insects.

In sites (A) and (B), (5) number of "whirl-like" scars in each tree was also recorded, and additional parameters were measured for each of the "whirl-like" scars: (6) rotation (either clock- or counterclock-wise), (7) up-and-down direction of the straight (or sinuate) scar connected with "whirl-like" one, (8) height above the ground, (9) size (as expressed by that divided by (π/4)), (10) compass direction and (11) exposure of xylem and the gallery through peeling-off of the phloem above it. Then, the trees were categorized with regard to parameters 2–5, and the "whirl-like" scars were categorized with regard to parameters 6–11.

Spatial distribution of "whirl-like" scars is quantitatively expressed with Lloyd's (1967) "mean crowding" and "patchiness".

Whole larval gallery observation.—In Hinoemata, Fukushima Pref., a blighted *A. mariesii* Mast. tree was felled on 24 Jun 1990 to expose the whole gallery made by a single larva. Also, at the *A. firma* plantation in Tama Forest Science Garden, FFPRI (MAFF), Hachiôji, one living tree (DBH 19 cm, 12 m high) was felled and cross-cut on 23 Aug 1993 to record the appearances, dimensions and

Table 1. Categorizations of *Abies* trees with regard to the parameters concerning the damage by *X. villioni* larvae in three forest sites, Tama Forest Science Garden, Hachiôji (A), Ashiu Kyoto University Forest (Section 33), Miyama (B), and a plantation in Kanahara, Imakane (C).

Locality Tree species	(a) Hachiôji *A. firma*		(B) Miyama *A. firma*		(C) Imakane *A. sachalinensis*
Resin exuded	19 (50%)[a]		12 (43%)[a]		16 (17%)[a]
Resin little or not exuded	19 (50%)		16 (57%)		77 (83%)
Straight and/or sinuate scar(s) present	31 (82%)[a]	31 (82%)	17 (61%)[a]	25 (89%)	
Straight and/or sinuate scar(s) indistinctly present	0 (0%)		8 (29%)		
Straight or sinuate scar absent	7 (18%)		3 (11%)		scars present: 25 (27%)[a]
With no "whirl-like" scars	14 (37%)[a]		14 (50%)[a]		scars absent: 68 (73%)
With 1 "whirl-like" scar	15 (39%)		5 (18%)		
With 2 "whirl-like" scars	6 (16%)		8 (29%)		
With 3 "whirl-like" scars	2 (5%)		1 (4%)		
With 4 "whirl-like" scars	0 (0%)		0 (0%)		
With 5 "whirl-like" scars	1 (3%)		0 (0%)		
Total	38		28		93

[a] Percent of trees examined.

shapes of all the "whirl-like" scars, as well as all the larval galleries within the trunk. The ages of the "whirl-like galleries" were estimated by counting the numbers of annual rings between each gallery and the cambium.

RESULTS

Spatial distributions of "whirl-like" galleries.—For the three forest sites investigated, the trees were categorized with regard to the presence of resin exudation, the presence of straight and sinuate scars, and the presence or the number of "whirl-like" scars on their trunks (Table 1, Fig. 4).

The spatial distributions of "whirl-like" scars in these forest sites in relationship to trees' DBH are shown in Tables 2 to 4.

We found that 17–50% of the trees investigated showed resin exudation, 82–89% of the trees possessed straight and/or sinuate scar(s) and 50–63% possessed "whirl-like" scar(s) (Tables 1–3).

Although the ages of the investigated forest stands vary considerably, in all the highest ratio of the trees with "whirl-like" scars was found in trees with 35–55 cm DBH (Tables 2–4), suggesting a definite tree diameter preference by *X. villioni* ovipositing females independent of forest age. The mean crowding value of the "whirls-like" scars in each DBH-class is low (Tables 2–3), except for the 2.31 value in the trees with 25–35 cm DBH in Hachiôji. Trees with 35–45 cm DBH had the highest value of mean crowding in Miyama. Lloyd's patchiness values ranged from 0.40 to 2.48 (Tables 2–3). The mean crowding value, and the ratio of trees with "whirl-like" scars suggest that the most susceptible trees have 35–45 cm DBH although there is a time lag of a few years between beetle oviposition and the appearance of scars.

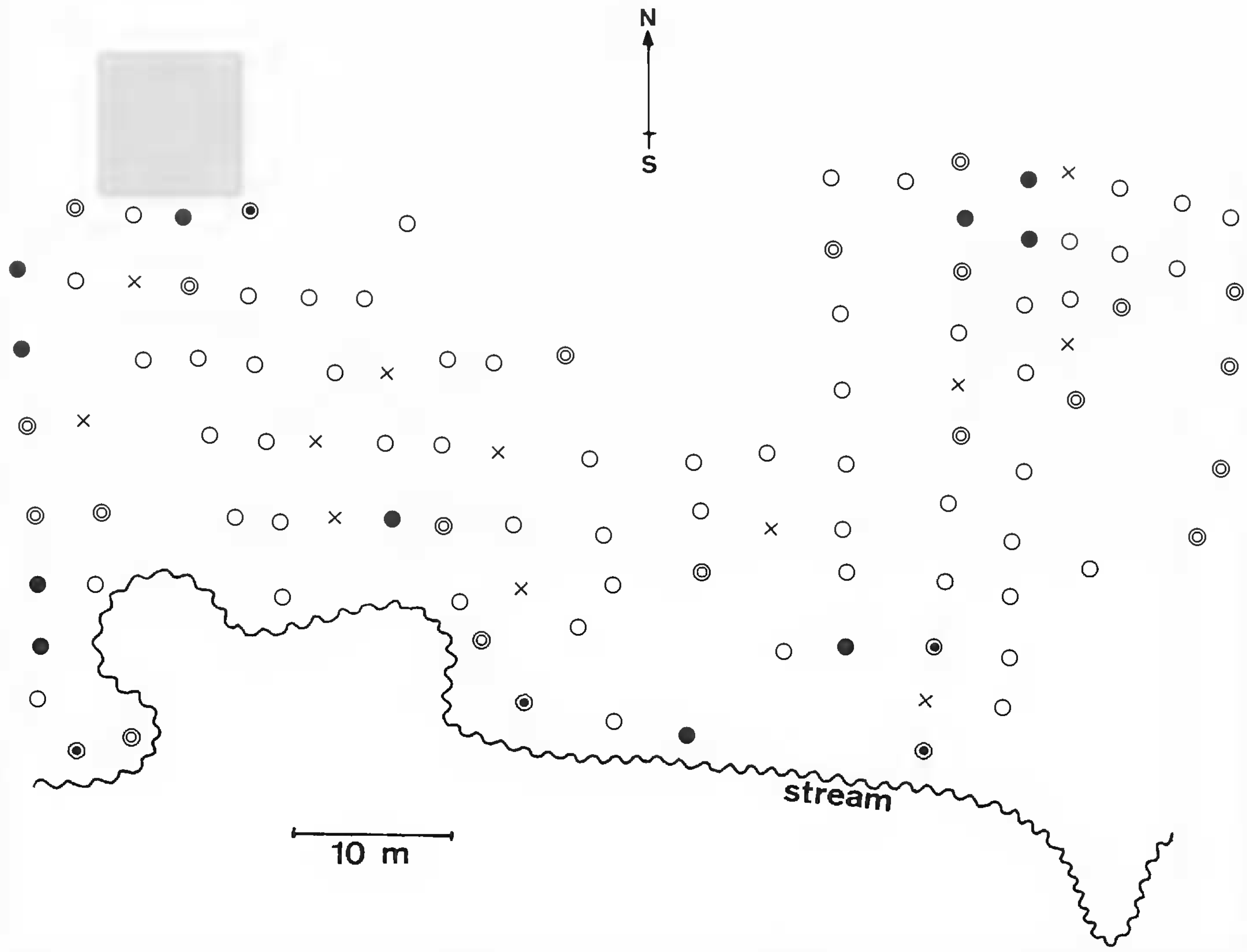

Figure 4. Overview of the distribution of *Abies sachalinensis* trees damaged by *X. villioni* larvae in a plantation, Kanahara, Imakane, Hokkaidô (C). The sign ○ represents a tree without scars or resin exudation, ● with resin exudation and without scars, ◎ without resin exudation and with scars, ⊙ with both resin exudation and scars, and × represents a dead tree.

The "whirl-like" scars were almost evenly observed to have either clock- or counterclock-wise rotation and to be either upward- or downward-connected. The size and the manner of presence of the "whirl-like" scars were shown to be highly variable (Table 5). The mean "whirl" size was larger in Hachiôji ($(251 \times \pi/4)$ cm^2) than in Miyama ($(179 \times \pi/4)$ cm^2), although the mean DBH of the trees (31 cm and 49 cm, respectively) shows the opposite trend.

The correlation between the presence of straight and/or sinuate scars and "whirl-like" scars on the trunk surface is shown in Table 6. The data show a positive significant correlation (Fisher's exact probability test, $P < 0.0005$): "whirl-like" scars are always accompanied by straight and/or sinuate scar(s), suggesting that a straight and/or sinuate scar without a "whirl-like" scar is indicative of larval mortality.

Statistical analyses found that most of the parameters measured are independent of each other at Hachiôji and Miyama, although the presence of straight and/or sinuate scar(s) are correlated to the presence and the abundance of "whirl-like" scar(s) (Fisher's exact probability test, $P < 0.01$ for all), and the presence of resin exudation to the presence of "whirl-like" scar(s) (χ^2-test, $P < 0.01$ for two sites). Also, there were no correlations among the presence of scars, presence of resin exudation, and trees' DBH at Imakane.

Whole larval gallery observation.—The gallery made by a single larva, found in the trunk of a blighted *A. mariesii* at Hinoemata (Fig. 5), had a length of

Table 2. Spatial distribution of "whirl-like" scars made by *X. villioni* larvae on *Abies firma* tree trunks in relationship to trees' diameter at breast height (DBH) in Tama Forest Science Garden, Hachiôji (A).

DBH range (cm)	5–15	15–25	25–35	35–45	45–55	55–65	Total
Number of trees (N)	0	11	14	10	3	0	38
Number of trees with "whirl-like" scars (N')	0	8	5	8	3	0	24
Ratio of trees with "whirl-like" scars (N'/N)	—	0.73	0.36	0.80	1.00	—	0.63
Total number of "whirl-like" scars ($\Sigma w_i = W$)[a]	0	10	13	10	5	0	38
Median value of the DBH range as expressed in meter (δ)	0.10	0.20	0.30	0.40	0.50	0.60	—
Total surface area of all trees as expressed in arbitrary area unit ($N\delta^2$)[b]	0	0.44	1.26	1.60	0.75	0	4.05
Number of "whirl-like" scars per arbitrary area unit ($W/N\delta^2$)	—	22.7	10.3	6.3	6.7	—	9.38
Number of "whirl-like" scars per a tree ($W/N = \bar{w}$)	—	0.91	0.93	1.00	1.67	—	1.00
Mean crowding of "whirl-like" scars ($\Sigma w_i^2/\Sigma w_i - 1 = \mathring{W}$)[a]	—	0.40	2.31	0.40	1.20	—	1.16
Lloyd's "patchiness" ($\mathring{W}/\bar{w}$)	—	0.44	2.48	0.40	0.72	—	1.16

[a] Let w_i be the number of "whirl-like" scars on each tree.

[b] Here, the real total area must be $\alpha N\delta^2$ in square meter, with the non-dimensional constant α representing a factor related to the taperness of the trees, supposing all the trees have the same α value.

112 cm, including 25 cm after the entrance into the xylem for pupation. The boring initiation point of the 1st instar larva and the top of the "whirl-like" gallery were situated 205 cm and 295 cm high above the ground, respectively.

A living *A. firma*, felled at Hachiôji, had seven independent larval galleries, of which four had "whirl-like" scars followed by pupal chambers. The appearances, dimensions, shapes and estimated ages of these larval galleries are summarized in Table 7. The formation of the "whirl-like" gallery, preceding pupation, can considerably damage the meristem, and a "whirl-like" scar can remain on the trunk surface for as long as 27 years after the formation of the larval gallery. The bark discs over some of the "whirl-like" galleries were peeled off, exposing the xylem surface.

Discussion

Lloyd's "patchiness" values (0.40–2.48; Tables 2–3) indicate that the "whirl-like" scars are distributed randomly and sparsely with the tree regarded as the sample-unit. Because the "whirl-like" scars represent a cumulative spatial distribution of mature larvae for as long as 27 years, the present distribution of existing larvae within the trees must be even sparser: the existing individuals of this species are distributed in an extraordinarily low density. This is not incompatible with the ratio of trees with "whirl-like" scars of 63% at Hachiôji or 50% at Miyama (Tables 2 and 3). The low density of existing beetles is supported by the

Table 3. Spatial distribution of "whirl-like" scars made by *X. villioni* larvae on *Abies firma* trees in relationship to trees' diameter at breast height (DBH) in Ashiu Kyoto University Forest (Section 33), Miyama (B). (For footnotes a and b, see Table 2.)

DBH range (cm)	15–25	25–35	35–45	45–55	55–65	65–75	Total
Number of trees (N)	1	4	6	2	10	5	28
Number of trees with "whirl-like" scars (N′)	0	1	4	1	5	3	14
Ratio of trees with "whirl-like" scars (N′/N)	0.00	0.25	0.67	0.50	0.50	0.60	0.50
Total number of "whirl-like" scars ($\Sigma w_i = W$)[a]	0	2	8	2	7	5	24
Median value of the DBH range as expressed in meter (δ)	0.20	0.30	0.40	0.50	0.60	0.70	—
Total surface area of all trees as expressed in arbitrary area unit ($N\delta^2$)[b]	0.04	0.36	0.96	0.50	3.60	2.45	7.91
Number of "whirl-like" scars per arbitrary area unit ($W/N\delta^2$)	0	5.56	8.33	4.00	1.94	2.04	21.87
Number of "whirl-like" scars per a tree ($W/N = \bar{w}$)	0	0.50	1.33	1.00	0.70	1.00	0.86
Mean crowding of "whirl-like" scars ($\Sigma w_i^2/\Sigma w_i - 1 = \overset{*}{W}$)[a]	—	1.00	1.25	1.00	0.57	1.00	0.96
Lloyd's "patchiness" ($\overset{*}{W}/\bar{w}$)	—	2.00	0.94	1.00	0.81	1.00	1.12

failure to capture any adult beetles during the field surveys conducted during the adult emergence season using either traps baited with kairomones and genus-specific sex pheromones (Iwata et al. 1991, 1992, 1993) or by visual searching. Because resin exudation indicates that the coniferous tree is inhabited by boring larvae, as has been demonstrated by Kobayashi (1982) for *Semanotus japonicus* (Lacordaire) infesting *Cryptomeria japonica* D. Don, just half of the trees in the forest site and 17-43% of the trees in other sites seemed to contain beetle larvae (Table 1).

The plantation site included open gaps, as well as many stumps made by cutting, suggesting that many young trees had been removed by felling due to lethal damage inflicted by *X. villioni* (Ganda et al. 1986). The damage by *X. villioni* took place on the edge of the plantation, reconfirming the observation of Kamijo & Suzuki (1973). This is not incompatible with the random and sparse distribution of "whirl-like" scars on trees because tree damage is viewed not within a single tree but over a forest section.

Table 4. Scars made on *Abies sachalinensis* trunks through boring activity of *X. villioni* larvae in relationship to trees' diameter at breast height (DBH) in Kanahara, Imakane (C).

DBH range (cm)	5–15	15–25	25–35	35–45	Total
Number of trees (N)	16	51	24	2	93
Number of trees with "whirl-like, straight and/or sinuate scars (N′)	4	12	8	1	25
Ratio of trees with scars (N′/N)	0.25	0.24	0.33	0.50	0.27

Table 5. Categorizations of "whirl-like" scars made by *X. villioni* larvae with regard to geometrical parameters in two *Abies firma* forest sites, Tama Forest Science Garden, Hachiôji (A), and Ashiu Kyoto University Forest (Section 33), Miyama (B). The numbers in some categories, when summed up, are inconsistent to the total number due to lack of data.

		(A) Hachiôji	(B) Miyama
Connected straight or sinuate scar[a]:	downward	19	5
	upward	19	17
(Height above the ground) = h:	800 cm ≦ h < 900 cm	1	0
	700 cm ≦ h < 800 cm	0	0
	600 cm ≦ h < 700 cm	5	0
	500 cm ≦ h < 600 cm	5	0
	400 cm ≦ h < 500 cm	1	2
	300 cm ≦ h < 400 cm	6	0
	200 cm ≦ h < 300 cm	7	5
	100 cm ≦ h < 200 cm	11	9
	0 cm ≦ h < 100 cm	1	8
(Size)/(π/4) = S:	$50\ cm^2 \leqq S < 100\ cm^2$	4	4
	$100\ cm^2 \leqq S < 150\ cm^2$	6	3
	$150\ cm^2 \leqq S < 200\ cm^2$	5	8
	$200\ cm^2 \leqq S < 250\ cm^2$	4	1
	$250\ cm^2 \leqq S < 300\ cm^2$	4	2
	$300\ cm^2 \leqq S < 350\ cm^2$	6	2
	$350\ cm^2 \leqq S < 400\ cm^2$	1	0
	$400\ cm^2 \leqq S < 450\ cm^2$	3	0
	$450\ cm^2 \leqq S < 500\ cm^2$	2	0
	$500\ cm^2 \leqq S < 550\ cm^2$	1	0
	$550\ cm^2 \leqq S < 600\ cm^2$	1	0
Compass direction:	North	3	1
	Northeast	6[b]	11[c]
	East	2	1
	Southeast	5	1
	South	6	2
	Southwest	9[c]	3[b]
	West	4	1
	Northwest	2	4
Phloem disc above the "whirl-like" gallery:			
Wholly peeled off ("whirl-like" gallery exposed)		8	—[d]
Partly peeled off ("whirl-like" gallery half exposed)		3	—
Recovered ("whirl-like" gallery covered)		26	—
Total		38	24

[a] Not significantly biased (Binomial test, $P > 0.05$) in (A), but biased to "upward" (Binomial test, $P < 0.05$) in (B).

[b] The study area is inclined to this direction.

[c] Not significantly biased to this (Kolmogorov-Smirnov's test, $P > 0.05$).

[d] Not checked.

Table 6. Correlation between the presence of straight and/or sinuate scar(s) and the presence of "whirl-like" scar(s) made by *X. villioni* larvae on each of the tree trunks at two *Abies firma* forest sites, Tama Forest Science Garden, Hachiôji (A) and Ashiu Kyoto University Forest (Section 33), Miyama (B).

Straight and/or sinuate scar(s)	(A) Hachiôji "whirl-like" scar(s)		(B) Miyama "whirl-like" scar(s)	
	Present	Absent	Present	Absent
Present	24 (63%)	7 (18%)	13 (46%)	4 (14%)
Absent	0 (0%)	7 (18%)	0 (0%)	11 (39%)[a]

[a] Including 8 trees only with very indistinct straight and/or sinuate scars.

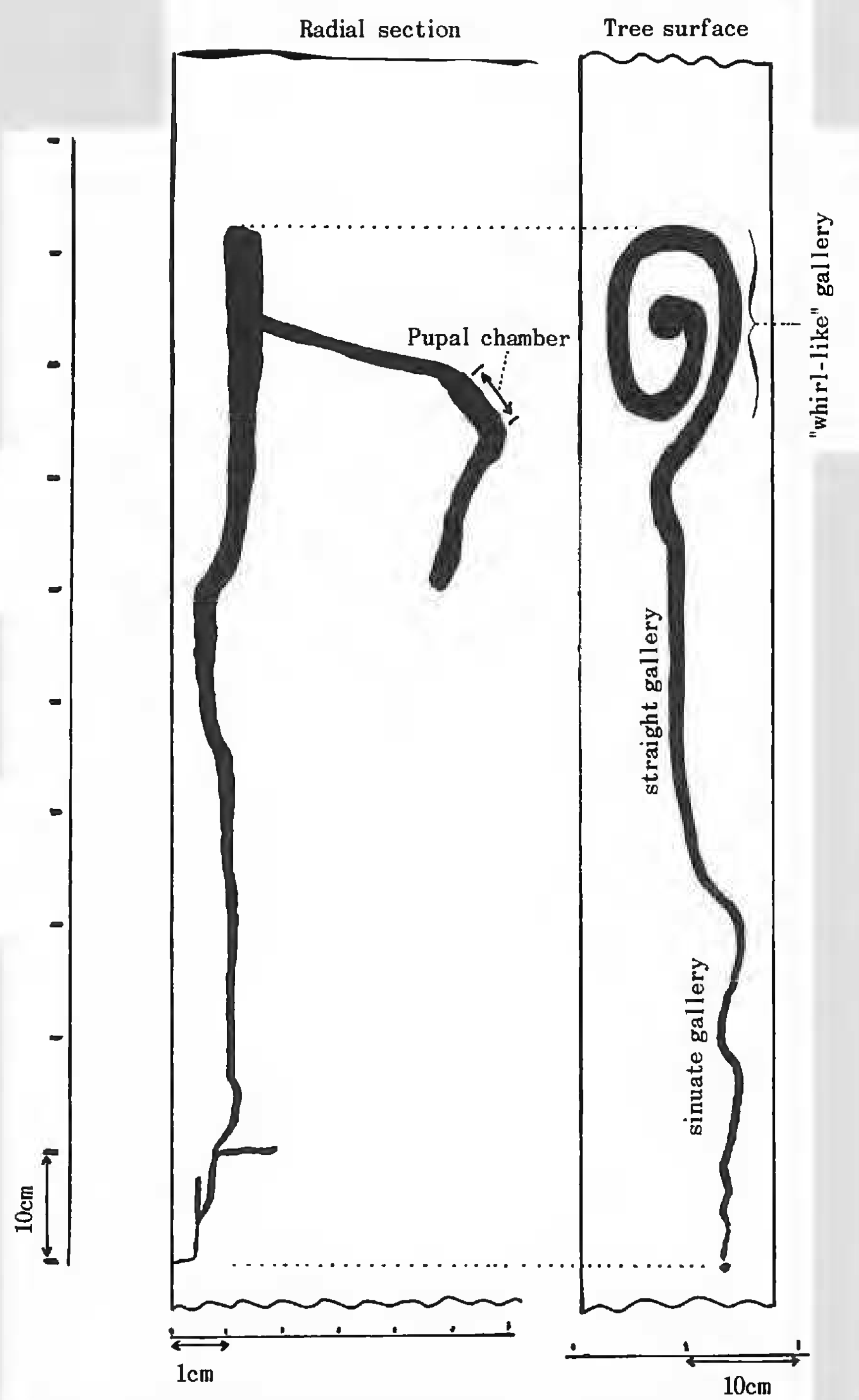

Figure 5. Whole gallery made by a single larva of *X. villioni* on a dead *Abies mariesii* tree-trunk. The tree, of 18cm DBH, was found in 1985, harvested on 24 Jun 1990 at the end of Toyasu Tributary Trail, Funamata Valley, Hinoemata, Fukushima Pref. and presumed to have been blighted in 1982.

Table 7. Four "whirl-like" scars made by *X. villioni* larvae on a living *Abies firma* tree sampled for the whole gallery observation, at Tama Forest Science Garden, Hachiôji (A).

Scar	A	C	D	G
Height above the ground (m)	2.1	3.5	3.7	11.6
Horizontal diameter × vertical diameter of the "whirl-like" scar (cm)	7 × 12	6 × 6	9 × 9	6 × 6
Appearance of the "whirl-like" scar	obscure	evident	evident	evident
Phloem disc over the "whirl-like" scar	wholly peeled off	recovered	partly peeled off	recovered
Total length of the connected straight and sinuate gallery (cm)	85	57	45	68
Presumed site of the initial larval gallery	branch (lost)	branch (lost)	branch (lost)	branch (lost)
Depth of the pupal chamber (cm)	9	6	8	5
Presence of the adult emergence exit hole[a]	−	−	+	−
Time elapsed since the formation of the gallery (years)	27–28	14–15	5	11

[a] +, present; −, absent.

The "whirl-like" scars tend to be distributed more densely in the lower part of the trunks although some in very high positions might have been overlooked to some degree (Table 5). This tendency in *X. villioni* infesting *A. sachalinensis* (Kamijo & Suzuki 1973) is known also in *S. japonicus* infesting *C. japonica*. In the latter species, this tendency has been ascribed to the change of bark roughness (Kobayashi & Yamada 1982). However, in *Abies firma*, by our visual inspection, the roughness of bark does not seem to be related to tree height.

The predominance of upward gallery connections to the "whirl-like" scars in Miyama (Table 5) is ascribed to the concentration of the "whirl-like" scars toward the bottom portion of the trunk. Although not significant, the compass direction of "whirl-like" scars on the tree-trunk is biased to the direction opposite to that toward which the study area is inclined, suggesting a possible strategy to avoid direct attack by natural enemies, such as picid woodpeckers (Iwata et al., in prep.).

The condition of phloem disc above the "whirl-like" gallery (Table 5) suggests that *Abies* trees are partly successful in protecting the severe wounds by cicatrization with phloem recovery. However, in some cases they fail in curing the "whirl-like" wound exposing the xylem, which presumably allows insects and fungi to invade the trunk.

Kamijo & Suzuki (1973) inferred a high mortality of *X. villioni* larvae boring within sound coniferous trees. The data on the presences of straight and/or sinuate scars and "whirl-like" scars on the tree trunk surface (Table 6) suggest that immature larvae, which are responsible for straight and sinuate scars, are not always successful in developing into mature larvae, which are responsible for "whirl-like" scars. At most only 77% of immature larvae formed "whirl-like" galleries. Further, of the four "whirl-like" scars within the tree sampled at Hachiôji (Table 7), only one possessed an adult emergence exit hole, suggesting a rather low probability of successful pupation to adult emergence. Further investigations are needed to clarify mortality factors acting during the immature stages of this species.

The low density of larvae and adults, and the low Lloyd's patchiness value suggest that little interference occurs among beetle adults or larvae.

Although *X. villioni* larvae cause damage to branches of host trees by boring (Iwata et al. 1990, Adachi 1995), the lack of branches and the presence of a complete gallery of one individual in the sampled dead tree in Hinoemata indicates that this species can complete its development only in the tree trunk.

Herein we have described the gross nature and spatial distribution of *X. villioni* larvae within tree trunks. Further investigations on the use of branches versus trunks by ovipositing females, movement of immature larvae from the branches into the trunk and a sensus of adult beetles are needed.

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